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Radiation Exposure and Cancer: Case Study

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The long, colorful, and tragic history of ionizing radiation and the use of epidemiologic approaches to characterize cancer risk distinguish this carcinogen from many other known carcinogens. Knowledge on the health effects of exposure of human populations to ionizing radiation is extensive, having mounted progressively through the 20th century. After their discovery in 1895, x-rays were used for 25 years by enthusiasts in applications ranging from treatment of acne and "female problems" to removal of unwanted facial hair (1). This enthusiasm persisted despite the scientific community's early knowledge of the adverse effects of x-ray overexposure at that time (1). The effects of extremely large exposures were first demonstrated by severe x-ray burns and cancer deaths among pioneering radiation workers. One of these pioneers was Thomas Edison's assistant, Clarence Dally, who helped develop the x-ray fluoroscope. After submitting to amputation of his burned and ulcerated arms, he died from cancer in 1904 (1).

The height of x-ray use was during World War I (1914–1918) when primitive mobile x-ray machines were used extensively in the field to locate shrapnel and help set broken bones (1). In the 1920s, young women painting watch dials with radium paint were found to have high rates of bone cancer from ingesting large quantities of radium when licking the brushes to make fine points (2). While this occupational hazard was eventually recognized (1, 3) and the practice of licking the paint brushes was prohibited by the late 1920s (3), use of ionizing radiation continued in many other applications for decades. For example, Thorotrast, a radiographic contrast agent consisting of thorium dioxide, was used from the 1930s to 1951, and exposed patients developed liver cancer and leukemia at high rates (4). In the 1940s, the first studies on leukemia excesses among radiologists were published (5–7). While the first warnings of adverse health effects were seen in radiologists, central in radiation protection has been the study of atomic bomb survivors. Findings of the initial studies of leukemia in atomic bomb survivors and other exposed populations were reported in the 1950s (8, 9). Nearly a decade later, the first quantitative estimates of lung cancer risk from cohort studies of underground miners exposed to radon were reported (10).

During the past 50 years, many other human studies have quantified cancer risks among persons exposed in military, occupational, medical, or environmental settings. These studies, along with confirming animal and other experimental data, leave no question as to whether radiation is a carcinogen. Several critical scientific issues remain to be resolved, however, including differences in risks for brief versus chronic exposures (i.e., is there a dose-rate effect?), the shape of the dose-response curve at low doses, the lifetime risk following childhood exposures, the possible existence of radiosensitive subgroups within the population (perhaps genetically determined), and the possible interaction between radiation and other carcinogenic exposures.

For over 70 years, standing committees have continually reviewed new data on radiation effects and recommended protection guidelines for workers and the public (11). The first recommendations for radiologic protection came from individual physicians, with little impact. Following a second wave of deaths in the 1920s due to leukemia and cancers with longer latency periods among the early radiologists and exposed patients, there were renewed efforts to institute safety standards for the use of radiation (1). Medical and radiologic societies in various countries finally took a lead in setting standards for radiation exposure (1). International agreement on guidelines for radiation safety was achieved in the second meeting of the International Congress of Radiology in 1928, when it formed the International Committee on X-ray and Radium Protection (11). This Committee, later to become the International Commission on Radiological Protection (ICRP) in 1950, issued guidelines approximately once every 3 years (11). While they were detailed, the guidelines remained arbitrary without the necessary data to assess safe levels of exposure (1). The United States counterpart to the ICRP, the US Advisory Committee on X-ray and Radium Protection, had its first meeting in 1929 (11). The Advisory Committee reorganized in 1946 to become the National

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Abbreviations: ALARA, as low as reasonably achievable; BEIR, Biological Effects of Ionizing Radiation; ICRP, International Commission on Radiation Protection; NCRP, National Council on Radiation Protection and Measurements; UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation.

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Committee on Radiation Protection (NCRP), which then became a formal council in 1964 with a charter from the US Congress and was renamed National Council on Radiation Protection and Measurements (11).

The ICRP's recommended limits for workers have decreased by a factor of 6 over the years, from 0.1 roentgen/day (approximately 300 millisieverts (mSv)/year) in 1934 to 5 rem/year (50 mSv/year) in 1956 (1). Today, the ICRP would allow 50 mSv in 1 year as long as the yearly average over 5 years is not more than 20 mSv. Recommended dose limits by the NCRP are similar to those of the ICRP, although differing somewhat in form. The NCRP also would permit 50 mSv in 1 year as long as the cumulative lifetime dose does not exceed 10 mSv multiplied by the person's age. Legislation by appropriate government regulatory bodies often follows the recommendations set forth by the ICRP and NCRP (12).

Both the ICRP and the NCRP rely heavily on the detailed scientific reports that come from two sets of periodically convened committees: the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the National Academy of Sciences/National Research Council committees on the Biological Effects of Ionizing Radiation (BEIR). In the 1950s there was growing public concern about radiation risks related in part to extensive nuclear weapons testing, such as in the Pacific Ocean where residents of several atolls had substantial fallout exposure. UNSCEAR was created in 1955 by the United Nations and still periodically reviews the extensive literature on the sources and effects of radiation exposure, publishing comprehensive reports. The National Academy of Sciences/National Research Council committees on the Biological Effects of Atomic Radiation published a series of reports during the 1950s. First convened in 1954 to review the available scientific knowledge on the effects of atomic radiation among living organisms, committees on the Biological Effects of Atomic Radiation were terminated in 1964 (13) and later replaced by BEIR.

In 1970, the Federal Radiation Council, whose activities were later transferred to the US Environmental Protection Agency, asked the National Academy of Sciences to prepare a report on information relevant to an evaluation of then current radiation protection guidelines. The first BEIR report was published in 1972 (14) in response to this request, and further reports have been published up to the present to address the health effects of exposure of human populations to low-dose radiation (4, 15–19).

The extensive uses of radioactive materials and of radiation across the last century led to development and support of an expansive community of radiation scientists and policy-makers, perhaps in part because of the ubiquitous but controllable nature of this exposure. Radiation is everywhere and can be found within the food we eat, the air we breathe, and the homes we live in. Even during air travel we are exposed to increased levels of cosmic rays. The medical uses of radiation are extensive, from diagnostic applications to the treatment of malignant diseases. Nuclear energy continues to be a source of power throughout the world to generate electricity. In order to balance the benefits of radiation uses with potential adverse health outcomes, a firm understanding of risks from these various exposures is essential.

Examples of the questions that society has grappled with around radiation risk include: Are nuclear weapons tests essential for national defense, and, if so, what are the ranges of risks from fallout or accidental detonations? Is the societal gain from electricity generated from nuclear power plants sufficient to balance the risk associated with long-term storage of high level radioactive wastes or of low-probability but deadly Chernobyl-like disasters? Is screening asymptomatic women for the early detection of breast cancer with mammographic x-rays worth the risk of potentially inducing malignancies among healthy women? How should underground uranium miners be compensated for the likelihood that their lung cancer was caused by radon exposure experienced in the mines? How does one compute the probability that radiation was responsible for cancer in an individual who received exposure from fallout during nuclear weapons testing, as a resident in a fallout impacted area, or as a participant in the weapons test as a soldier? Is radon in homes a serious public health hazard, and should testing be mandatory? What is the risk of using plutonium generators in spacecraft that might explode before leaving the earth's atmosphere? If genetic testing uncovers groups who are sensitive to the induction of cancer by radiation, should radiation guidelines be lowered or should such individuals be prohibited from working with radiation?

RADIATION SCIENCE AND POLICY TODAY

Scientific data regarding radiation risks

The basic mechanism by which ionizing radiation causes damage to living matter is well known. Ionizing radiation has sufficient energy to break the electronic bonds that join atoms into molecules. Consequently, ionizing radiation can cause damage to living cells and organisms resulting in genetic effects, cancer, and other somatic effects. The mechanisms follow basic radiophysical principles, and there has been some understanding of the radiobiologic effects of the agent for almost 100 years (3, 17, 18). Several questions still remain, but the extent of understanding of this agent's effects is much greater than for most chemicals.

Epidemiologic data have driven the assessment of radiation risks (20, 21). Epidemiologic studies included occupational groups, such as radiologists, radium dial painters, and uranium miners, exposed to different forms of radiation (2, 5–7, 10), as well as individuals exposed to radiation as a therapeutic agent (4, 22–25). The types of radiation exposure, the dose, and the duration of exposure differed in these studies. The studies came from different parts of the world, yet the data indicating a risk of cancer in humans were generally mutually compatible and consistent with findings from animal exposures and laboratory experiments (3).

One of the major sources of epidemiologic data for risk assessment has been the longtime prospective cohort study of the atomic bomb survivors in Japan (26). This study has proved invaluable because the population is large and includes persons exposed at all ages, including in utero. Of course, the exposure for this population was almost entirely

to a single high dose of radiation. A select group of survivors, numbering approximately 87,000, has been followed since the 1950s; dose estimates have been derived for each individual and the survivors are followed for incident cancers and other diseases and mortality (27, 28). Follow-up has been maintained to the present by the Radiation Effects Research Foundation and its predecessor, the Atomic Bomb Casualty Commission. The data are periodically analyzed to track the cancer risk associated with radiation exposure. As follow-up has lengthened, the data are increasingly informative concerning the time course of the excess cancer risk associated with radiation (29, 30). Risk estimates from the cohort have been continually refined and updated as follow-up has lengthened, statistical analysis methods have become more sophisticated, and dose estimates have been revised. The study remains the strongest source of data for estimating risks of low linear-energy transfer (LET) radiation. Additionally, as more radiation-exposed populations have been studied, risk estimates from them have been generally consistent with those in the atomic bomb survivors.

Thus, in the case of ionizing radiation, there is a wealth of scientific data on risk, supported by biologic theory and laboratory data. The cancer risk is well accepted, although there is controversy over risks at low doses and dose rates. Differing risk for different organs is well established. Perhaps the major controversy at present is the shape of the dose-response curve at low doses and dose rates; this topic is being addressed by the current BEIR Committee (BEIR VII). The epidemiologic data are increasingly informative as follow-up of the existing cohorts continues.

Committees for science and policy reviews

Standing committees on radiation have continued to meet periodically and their reports have provided key guidance to governmental agencies in the United States, Europe, and elsewhere. The BEIR and UNSCEAR committees, for example, have reviewed and evaluated the scientific evidence, developing new risk models and risk estimates and characterizing uncertainties. Committees such as the NCRP and ICRP have used these risk models to assess whether current policies and standards set an acceptable level of safety for the public and for workers. Typically, these committees have included the full range of scientists involved in understanding radiation risks—epidemiologists and statisticians, radiobiologists, health physicists and dosimetrists, and others. The work of these committees has generally been neutral to policy implications and free of pressure from regulations, the regulated community, and the public. More recently, however, controversy concerning radiation risk has become stronger and more strident, even reaching into the appointment of the BEIR VII Committee.

Public perception of radiation

The public has an understanding that radiation poses a cancer risk, but the range of views extends from a general acceptance of medical exposures to widespread concern about the risks of some sources, such as nuclear power generation. Thus, the public is typically unquestioning of medical uses for screening, diagnosis, and therapy. Exposure to radiation from many other sources, however, may be regarded with an almost unreasoning fear, as occurred, for example, with the irradiation of food as a method of sterilization. This fear probably originates, in part, with the mystique of radiation and the involuntary nature of many exposures and the possibility, however remote, of a catastrophic disaster. In fact, the Three Mile Island episode and the Chernobyl disaster support this concern, providing widely publicized evidence that low probability, but potentially lethal, events can take place. The extensive scientific evidence on radiation risk has not successfully dispelled these fears. Paradoxically, the information on the potential lung cancer risk from indoor radon has motivated only a small minority of US homeowners to measure radon levels in their homes and to carry out mitigation if needed (31, 32).

REMAINING ISSUES

Science questions remain

Despite a wealth of epidemiologic data, supplemented by a large body of laboratory evidence on the effects of radiation at the molecular, cellular, and whole animal levels, important questions remain with regard to the risk of cancer induction by radiation. The questions include a broad range of issues from biologic effects, such as whether normal DNA repair mechanisms are sufficient to reverse radiation damage at the lowest doses and dose rates, to interactive effects of radiation with other agents, to whether there are unrecognized non-cancer, non-genetic endpoints.

The most contentious issue in radiation risk assessment revolves around the estimation of risks at very low doses and dose rates—small increments of exposure only slightly above natural background radiation. Risks in this dose range cannot be studied with sufficient precision by direct epidemiologic investigation, although epidemiologic studies of populations accumulating moderate-to-high doses of radiation over an extended time can inform the discussion of risks at low doses. For public health protection, another important issue is the possible existence of groups more susceptible than average to the harmful effects of radiation. This sensitivity might arise from a genetic basis, from synergism of radiation with other carcinogens, or from inherent biologic characteristics like age and gender. It is likely that some individuals are genetically predisposed toward radiation-induced cancer. A number of genes have been investigated and the new approaches of molecular and genetic epidemiology should provide further insights, particularly when combined with the technologic advances for studying the genetic basis of disease. Sensitivity through synergism is illustrated by the example of radon and smoking increasing the risk of lung cancer. Thus, the risks of the mixed chemical and radiation exposures associated with nuclear waste clean-up need to be better understood. Finally, there is renewed interest in the possibility that moderate doses of radiation might cause delayed, non-cancer health effects such as cardiovascular disease.

There will always be some imprecision in radiation risk estimates and uncertainty associated with the models used to

derive the estimates. These uncertainties need to be fully characterized so that their implications for risk management are clear, both to policy-makers and the public. There are improving techniques for this purpose. Careful review and integration of epidemiologic and radiobiologic results will lead to more certain models and accurate depiction of assumptions and attendant uncertainties. A comprehensive listing of uncertainties offers an appropriate framework for advancing a policy-relevant research agenda. The process of uncertainty analysis also can be used to assess the relative importance of various sources of uncertainty, which can help guide future research.

Policy issues remain

Harmonizing radiation and chemical risk management. For historic reasons, radiation risk assessment and management have developed under a different paradigm than is applied to risk assessment and management for chemical carcinogens. Data on chemical carcinogens are generally derived from animal studies, while radiation data are mainly from human studies of cohorts, such as the atomic bomb survivors, uranium miners, and patients medically exposed to radiation. The risk management approaches for chemicals and radiation differ fundamentally in their goals. Chemicals are evaluated individually, and the aim is to set standards to keep risks for each below 10^{-6} if possible. Occasionally it is not possible to set standards to maintain this low risk because to do so would deny benefits to the population. In that case, standards will be selected to keep risks at least below 10^{-4} at the most. The paradigm for radiation risk management is based on the principle of "as low as reasonably achievable" (ALARA), and this principle is subscribed to by the National Research Council and US Department of Energy. After all sources of ionizing radiation exposure are considered in setting a maximum dose limit, ALARA is then applied to reduce the risk, which involves "making every reasonable effort to maintain exposures to ionizing radiation as far below dose limits as practical…" (33).

Difficulties have arisen when the US Environmental Protection Agency or other regulatory agencies have applied the paradigm for risk management of chemicals to a radiation issue that would have been handled under the radiation paradigm. For example, applying US Environmental Protection Agency's paradigm for chemicals and treating the current radiation dose rate limit of 100 millirems per year as a standard would result in an unacceptably elevated lifetime risk of about 3 in 1,000 for exposures at the standard (34). This approach assumes that population exposure would be at the dose limit of 100 millirems per year over a lifetime. Applying the radiation paradigm, however, exposures and associated risks would be much lower over the lifespan for most people with the ALARA principle in effect (34).

Influence of public perception of acceptable and actual risks of radiation on policy. Risk perception studies have consistently shown that the general public ranks radiation risks higher than many risks that have lower rankings when evaluated with existing quantitative risk assessment techniques. Although it is clear that many of the public are simply unaware of the quantitative information available, it is widely believed that the public also incorporates characteristics of risk, such as dread or unfamiliarity, that are not captured in the quantitative analyses (35). Whether or not such behavior is "rational" is debated, but clearly it must be considered in the development of policy.

It is also clear that the public is more accepting of radiation risk (as quantitatively determined) in the medical arena than in the environmental arena. Most of this difference is probably attributable to the closer coupling of risks and benefits in the medical uses, involving a voluntary acceptance of risk rather than the external imposition of risk. Whether the advice of the physician is appropriately balanced in regard to risks and benefits is a challenging question.

Qualitatively, the public may be less accepting of nonmedical radiation risks than of chemical and other risks, based on its relatively strong opposition to nuclear power and its aversion to nuclear waste depositories. Whether epidemiology has a role to play in clarifying this issue is unclear, and educating the public on the extent of the evidence available and its subtleties may be difficult. Currently available methods are unlikely to have the power to discern whether or not a reactor or waste depository is affecting the surrounding public. However, the more important question to answer is how large an effect might be credible in a given situation based on known scientific evidence updated constantly with new information. If the possible risk is small, then a definitive answer on whether an effect exists is not meaningful. Unfortunately, model-based predictions that the probability of cancer is low around such facilities do not seem to have much weight with the public or even with some health physicists.

Lack of effective interaction between epidemiologists and policy-makers: practical implementation of policies. The interaction between epidemiologists and policy-makers could be improved. First, epidemiologists working on radiation risk should be cognizant of the likely application of their findings by policy-makers. Results should be presented in such a way that the implications for policy are clear and balanced. Uncertainties should be fully discussed and the results placed in perspective with respect to those obtained from other studies. In fact, the relatively small cadre of epidemiologists working on radiation generally have sensitivity to these issues.

Second, policy-makers may be confused by seemingly conflicting epidemiologic results. Individual studies may be inappropriately presented in a dichotomous fashion as "positive" or "negative." Epidemiologists can assist the policy-maker in evaluating the quality of studies in relation to their interpretation for policy issues. Additionally, new approaches to data synthesis by meta-analysis and pooling of data combine evidence in a useful way for policy-makers and provide a framework for evaluating the contribution of new evidence. Measurement error models provide insights into the degree to which risk estimates are biased by the unavoidable misclassification of exposure in epidemiologic studies.

Third, epidemiologists can be helpful to policy-makers at the point of implementation. In particular, epidemiologists possess tools for assessing the population impacts of alter-

native policy choices and can aid in communicating risk information to the public.

LESSONS LEARNED

The example of ionizing radiation offers several useful "lessons" concerning epidemiology and policy. First, there is a relative abundance of data, far more than will ever be available for most chemical carcinogens. Nonetheless, new questions have continued to challenge epidemiologists and epidemiologic data. Over recent decades, emphasis has shifted from estimating risks to evaluating modifiers of the risks, particularly dose-level (low versus high) and dose-rate. Epidemiologic studies can contribute to these issues but complementary laboratory data are needed, particularly as laboratory findings point to mechanisms that should be incorporated into the structure of risk models.

Second, the control of radiation exposures has been improved by informed use of the epidemiologic evidence. The periodic review of the evidence by scientific review committees has enhanced acceptance of both the scientific data and regulatory standards arising from the data. Implementation of increasingly stringent standards has driven down radiation exposure levels, especially from occupational and environmental sources. In addition, the development of effective real-time monitoring systems for use in industry has resulted in lowered occupational exposures. Although there may be ways to bypass these monitoring systems and regulations, the more effectively we can build information systems which provide ready access to exposure data for individuals and businesses, the harder it is to escape the protective regulations.

Third, we have learned that communication of scientific results and the related uncertainties in risk numbers is a difficult and only partially solved problem. Scientists may be ill-equipped to approach these issues as few are formally trained in risk communication, having learned instead through experience. Only now is the scientific community beginning to address the issues of effective communication and what are the factors, the situations, and the tools by which scientific information can be best transmitted (36). Communicating the concept of uncertainty may be particularly challenging for scientists, as well as reaching a "bottom line" in the face of uncertainty (37). Different audiences will have differing needs to understand uncertainty and its implications (36). Thus, needs of fellow scientists, policy-makers, the media, and the public may differ substantially. The media may not be trying to gain knowledge but may be seeking information which can be "used" to justify the thrust of a story, such as the need to clean up an existing waste dump (37). The community stakeholders may be seeking firm answers and not explanation and calls for further research.

As in most areas of research dealing with environmental problems, a multidisciplinary approach is essential. However, science has long been compartmentalized into disciplines that have their own culture, language, and funding sources. There is little incentive offered to diverge from this structure and to address problems in a truly multidisciplinary fashion. Committees like the BEIR Committees bring together multidisciplinary groups, and this diversity is critical for synthesis. Mechanisms need to be found for encouraging this same breadth in research groups.

Scientists may confuse their role in policy debates and overstep by proposing what is proper for the public to know or what risk management option is optimal. Instead, scientists should communicate openly and serve as a resource for the community and policy-makers in order to identify their needs and concerns and to help answer those needs. This interaction is critical for all parties.

The field of radiation science has clearly been subject to the dictum that "policy drives funding and funding drives science." Radiation sciences have advanced over the years producing a wealth of knowledge, new methodologies, and innovation and technology. However, support is waning even as questions about risk remain unanswered. The boom of research and research funding that was driven by medical and military uses and power generation is long over. Much of our understanding of fundamental radiology and health physics was gained during the boom period. Key cohorts were initiated at that time. However, subsequent cycles and a general decline of support have reduced the role of involved scientists, and few new researchers are entering radiation sciences. Given the substantial lag needed to renew the pool of scientists, there is the possibility of future crises when critical issues need rapid answers. Methods of providing stable scientific support are needed.

As we enter the next millennium there will undoubtedly be new and difficult issues surrounding the uses of radiation, and the interface between policy and science will remain critical for protecting the public's health. As before, judgments on radiation issues will take into account the best scientific evidence available, and there will be a continuing need for evidence on radiation risks. To this end, it is encouraging that the Department of Energy has initiated a new program to train radiation scientists at the University of Pittsburgh, that Harvard University has expanded its program in radiation research, that the National Cancer Institute and the Centers for Disease Control and Prevention have retained programs in radiation epidemiology, and that the ICRP, NCRP, UNSCEAR and BEIR committees remain strong and influential.

RECOMMENDATIONS

Changing technologies and applications in radiation science will bring emerging issues to the forefront. Over 50 years after the development of massive nuclear weapons complexes in the United States, the former Soviet Union, and other countries, there is now the challenge of safely managing wastes, assuring that workers are not placed at undue risk, and that radioactive materials can be safely stored for centuries. Because the potential exposures from radioactive waste depositories are likely to be at low doses and dose rates, answering questions about this area of the dose-response relation becomes even more important. Meanwhile, the expanding use of radionuclides and external radiation in diagnostic imaging and nuclear medicine (radiopharmaceuticals) challenges policy-makers with decisions about risk-benefit trade-offs in the medical arena.

With such emerging issues still to be addressed, several recommendations are offered based on the lessons learned over the past 70 years of radiation science and policy-making.

1. A stronger emphasis on helping epidemiologists and other radiation scientists to more effectively communicate with the media, the public, and policy-makers

Epidemiologic research addresses questions about health among human populations; epidemiologic studies are often of interest to the general public, and research results are increasingly reported in the mass media. Consequently, epidemiologists are frequently called upon to present their findings directly to audiences of affected stakeholders or to print, television, and radio reporters. Government officials and decision-makers rely heavily on the news media for information related to science and health policy. Arguably, the most direct route to improving the translation of epidemiology into sound public policy is to emphasize the importance of communications skills in epidemiologic training programs and to offer practicing scientists continuing education in such skills.

The ability to convey clearly and succinctly the results of scientific research verbally and in writing has become a critical skill for epidemiologists. As reporters with limited technical backgrounds cover stories with epidemiologic content or consult epidemiologists for "expert" views on newsworthy science, and as policy-makers rely more and more on the mass media as a primary source of scientific knowledge, it is important that epidemiologists become proficient at interacting with members of the media, lest distorted or misinterpreted science become the basis for public belief or policy decisions. The idea is not to make every holder of a Ph.D. the host of their own Discovery Channel program, but to acquaint students with the rules of media engagement, to equip them with basic public speaking skills, and afford them some practice addressing groups in front of microphones and cameras with the opportunity to review videotapes of their performance.

Epidemiologists consider that journalists should be a target for education. Teaching opportunities might include developing classes for journalism students. Symposia targeted at science writers are conducted by special groups but this effort should be expanded to encompass small newspapers and media groups. This may be an effective way of providing education before a controversial issue challenges rational responses.

Communication is a two-way street. Policy-makers and the public would benefit from more skilled and attentive listening on the part of the scientific community. Scientists engaged in epidemiologic research should carefully consider the impact that proposed studies might have on affected communities and arrange to communicate the intent and limitations of studies before they are initiated. As epidemiologists pursue questions entwined with controversial policy issues, they must learn to interact constructively with worried community members and skeptical representatives of the press. The problem is that public concern may not be a response only to hazard but a combination of "hazard and outrage." The outrage arises against companies or government groups when the public believes that these organizations have behaved inappropriately in the face of a hazard. The experience of confronting these angry audiences is dismaying to many scientists who may then avoid further such interactions even though there is a pressing need for scientists who can clearly and credibly articulate the public health issues entwined in controversial situations. Epidemiologists would benefit from basic training in how to constructively engage groups in emotionally charged settings, and from exposure to "lessons learned" anecdotes from colleagues or professionals who work frequently in the public realm.

2. Change organizational structures to support/promote interdisciplinary teams

Many of the problems probed by epidemiology are complex, multifaceted issues that require investigation by, and collaboration among, scientists and experts from several different technical disciplines. The fruits of such multidisciplinary efforts can be bountiful, but the logistical and emotional difficulties of working in a team environment is often overlooked. Scientists from different disciplines may speak different languages and work from different assumptions. Communication between radiation epidemiologists and health physicists, for example, is often problematic. Even seemingly simple concepts, such as "radiation dose," may pose significant translation problems that take time and patience to resolve. Such realities of interdisciplinary work need to be reflected in timetables for research and scientists' schedules.

In spite of the fact that most epidemiologic studies with implications for public policy are multidisciplinary investigations, the administrative and incentive systems of academia remain narrowly focused on specific disciplines. Existing institutional structures and expectations may discourage rather than support the teamwork that is increasingly a central aspect of epidemiologic research. Thus, promotion and tenure depend on publication in specialty journals and citations as the "first author" of peer reviewed studies. Contributions made as part of a team that undertakes a significant multidisciplinary research project are not accorded the same respect. Similarly, active participation in policy-making, such as service on expert panels, providing Congressional testimony, or aid in drafting legislative language are not generally recognized as worthy credit or reward within academia. Funding sources are keyed to discipline-specific departments and divisions, and it is often difficult to "share" money or research support among institutional duchies and kingdoms. Scientific journals are devoted to specific disciplines and subdisciplines and rarely feature in-depth examinations of all facets of complex scientific and policy issues.

Universities and funding sources should re-examine how their organizational structures and practices support or penalize multidisciplinary research. Consideration should be given to supporting conferences, journals, and seminars that explicitly consider the multidisciplinary nature of many important epidemiologic studies and potential studies and seek ways of encouraging and supporting scientists from different fields to work together efficiently.

3. Support forums and journals that address science and policy aspects of complex public health problems

The absence of a common forum wherein scientists and policy-makers could examine and review the different facets of complicated public health issues has limited the usefulness of science to decision-makers and stunted the creation of innovative policy.

It is difficult for anyone to obtain a comprehensive and coherent picture of the scientific and policy aspects of most major public health issues. There is, for example, no simple way to review the current debate about "mercury toxicity" that has been occupying many university scientists and policy-makers at the US Environmental Protection Agency short of reading hundreds of pages of testimony and government documents. Even then, one is left to infer most of the policy issues and options and to chase down unclear scientific references. Scientists often present data with only a sketchy understanding of policy concerns or the available options for government action. Decision-makers for their part frequently pursue policy "solutions" with an incomplete or erroneous understanding of the underlying science. If researchers do not fully comprehend the pertinent policy questions and options, they may pursue questions that are not relevant to the pending decisions or are unnecessarily detailed, too imprecise, or otherwise off the mark. Decision-makers must have sufficient knowledge of science to engage in a constructive dialogue about what studies might be useful in formulating sound public health policy, and must understand the limits of available knowledge and attendant uncertainties.

DISCLOSURES

Dr. Genevieve Matanoski is Professor of Epidemiology at the Johns Hopkins Bloomberg School of Public Health. A major portion of her epidemiologic research studies have been focused on environmentally-induced cancers, especially those related to radiation exposure. The studies have included risks to workers from ionizing radiation in occupational settings in medical facilities or shipyards where nuclear-powered ships were overhauled. Her studies of risks in children from therapeutic radiation has also offered important public health information regarding medical uses of radiation in treatment of the young. Dr. Matanoski has served on several scientific committees which have reviewed the hazards associated with radiation and other environmental issues, including the Science Advisory Board of the US Environmental Protection Agency where she served as Chair of both the Radiation Subcommittee as well as the Executive Committee. She has testified before Congressional committees of both the House and Senate on the hazards of radon as a public health issue and the implementation of recommendations for household testing.

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Dr. Ethel Gilbert is a biostatistician in the Radiation Epidemiology Branch of the National Cancer Institute. Her research has included studies of nuclear workers, radiation risk assessment, and studies of second cancers after radio- and chemotherapy. Dr. Gilbert currently serves on the National Academy of Sciences Committee on Health Risks from Exposure to Low Levels of Ionizing Radiation (BEIR VII), and previously served on the Committee on Health Effects of Exposure to Radon (BEIR VI). She is a fellow of the American Statistical Association and a member of the National Council on Radiation Protection and Measurements.

Dr. Tara O'Toole is currently the Deputy Director of the Johns Hopkins University Center for Civilian Biodefense Studies and a member of the faculty of the Bloomberg School of Public Health. The Center is dedicated to informing policy decisions and promoting practices that would help prevent the use of biologic weapons. From 1993 to 1997, Dr. O'Toole was Assistant Secretary of Energy for Environment Safety, serving as principal advisor to the Secretary of Energy on matters pertaining to protecting the environment and workers and public health from US Department of Energy operations. During her tenure, she conducted four major "Vulnerability Studies" that identified major safety and environmental hazards at the nation's nuclear weapons complex, and led a multi-agency, multi-million dollar task force that oversaw the government's investigations into human radiation experiments conducted during the Cold War. From 1989 to 1993, Dr. O'Toole was a Senior Analyst at the Congressional Office of Technology

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Dr. Jerome Puskin is the Director of the Center for Science and Risk Assessment in the Office of Radiation and Indoor Air at the US Environmental Protection Agency. In this capacity, he is responsible for making quantitative estimates of the health risks from ionizing radiation and their uncertainties and for developing documentation which explains the scientific basis for these estimates. These estimates and documentation are used to support US Environmental Protection Agency actions to limit public exposure to radiation.

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